"On the Compressibility of Solids." By J. Y. BUCHANAN, F.R.S.

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The solids dealt with in this research are the metals platinum, gold, copper, aluminium, and magnesium. Their absolute linear compressibilities were directly determined at pressures of from 200—300 atmospheres at temperatures between 7° and 11° C. The determinations were made by the same method, and with the same instrument which I used for the determination of the compressibility of glass in 1880.* As nearly a quarter of a century has passed since then it will be expedient to recall the principal features of the instrument, and of the method.

The idea of it occurred to me on the evening of March 23, 1875, the day on which the "Challenger" made her deepest sounding, namely, 4475 fathoms (8055 metres), and I was able to put it in practice 6 days later, on March 29, when, however, the depth was only 2450 fathoms (4410 metres). The observations which I was making during the voyage on the compressibility of water, sea-water, and mercury, were of little value without a knowledge of the compressibility of the envelope which contained them. It was a matter to which I had given much thought. I had studied all the methods which had been used up to that date, but they had all turned out to be faulty.

The idea of utilising the linear compressibility of glass in order to arrive at its cubic compressibility had occurred to me, as it had, no doubt, occurred to many others, before. The difficulty lay in giving the idea experimental expression. It was clear that the instrument would fall to be classed as a piezometer, and would have to be a self-registering one, because what takes place in the depths of the sea is removed from observation. All my piezometers contained a liquid, and this I had recognised to be fatal to absolute measurements. The problem had, therefore, come to be: to design a piezometer which should contain no liquid; and it was the solution of this problem which occurred to me on the evening of March 23, 1875.

The form which the instrument took was very simple. In my laboratory outfit I had included some lengths of tubing suitable for the stems of piezometers, of which I had to make a number during the voyage. In order to be able to use the indices of broken deep-sea thermometers, the tubes had the same internal diameter as the stems of these instruments, about 1 mm. On the outside of the tubes a scale of millimetres was etched. I took the greatest available length of this tube, namely 60 cms. I then drew out a wire of the same glass and passed it into the tube until it appeared at the other end of

* 'Roy. Soc. Edin. Trans.,' vol. 39, p. 589.

the tube. This end of the tube was then sealed up, and the end of the glass wire was fused into it, so that, while free throughout its whole length, longitudinal motion was prevented. The length of the glass wire was 57 cm., so that there was an empty space in the tube of 3 cm. above it. The magnetic index of a broken deep-sea thermometer was re-haired and passed into the tube above the glass wire. The open end of the tube was then sealed up. The result was a piezometer consisting of nothing but glass. In principle it was precisely the same as any of the other piezometers. The indices of these give the difference between the compression produced by the pressure on the contents and on the envelope. In the case of the other piezometers, which contained liquids, the balance was on the side of the contents. In the all-glass piezometers the contents, besides being of the same material as the envelope, were completely protected from pressure, and the whole of the change of length measured fell to the envelope. It has, therefore, a feature which is possessed by no other instrument; with it the absolute compressibility of a solid is determined by one measurement.

Before the instrument was attached to the sounding line, the index was brought down by means of a magnet to rest on the end of the internal glass wire, exactly in the same way as if it had been the mercury column in a *maximum* and *minimum* thermometer. The instrument was then sent to the bottom, or to whatever depth might be decided on.

During the descent the temperature of the glass, both inside and outside, fell with that of the water through which it passed, but as the contraction produced was the same on the wire and on the tube, there was no differential effect to be recorded by the index. On the other hand, the increasing pressure, as the instrument descended, affected only the outside tube, which it shortened. In contracting, it was obliged to pass the index, which was kept in its place by the internal wire. When the instrument was being hove up, the reverse process took place; the tube lengthened, and lifted the index clear of the internal wire by an amount equal to the lengthening of that portion of the tube. As the whole clearance produced by the expansion from the greatest depth did not exceed 1 mm., its amount had to be estimated by the eye with the assistance of a magnifying glass.

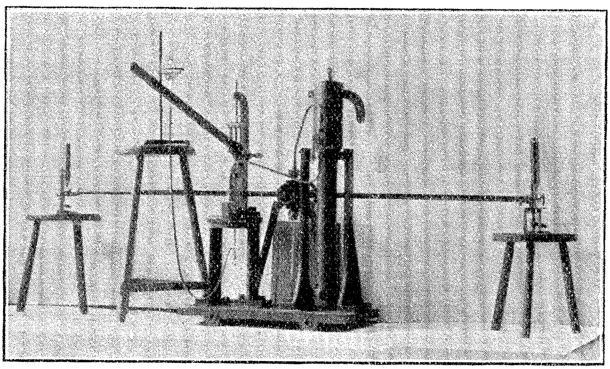
The experiment made on March 29, 1875, was quite successful, and it gave 3·74 as the cubic compressibility per million per atmosphere, of the glass of which the tube was made. The exact figure found in 1880 for glass from the same source was 2·92. A number of observations were made with the instrument, both on the sounding line and in the compression apparatus with which the ship was supplied, and figures from 3—5 per million were found. These were sufficient to give the order of the constant which was sought, but it was impossible

with the appliances at hand to measure such small distances with sufficient accuracy to enable a definite value to be determined.

On the return of the ship I embodied the principle in an instrument of precision, which I had constructed in the early part of 1880, and I used it in the month of June of that year for the exact determination of the compressibility of the glass which had been used in the construction of my "Challenger" piezometers.

It is this instrument, and without any alteration, which I have used for the purpose of the present research.

FIG. 1.



With the assistance of fig. 1, its features, and the distribution of its parts, will be apparent without any lengthy description. It consists of three parts: the force pump on the left, the receiver for the reception of piezometers or other bodies on the right, and behind these, the block with tubes projecting on either side to receive the rod or wire of the solid, the compressibility of which is to be determined. Every part of the instrument is made of steel. The part which most concerns the present research is the steel block, in the rear, with tubular prolongations. When the rod or wire to be experimented with has been introduced, the ends of the tubes are closed with thick glass tubes, which are kept in their places by open steel caps. Each of these tubes is commanded by a microscope with micrometer eye-piece. In 1880, when the instrument was housed in a room with a stone floor, these microscopes stood on three-legged stools, as shown in the figure. As the room with the stone floor was no longer available, I had to instal the instrument close to the windows of the laboratory, which has a wooden floor, and fix metal brackets in the wall to carry the microscopes. In both cases the micrometers, which measure the expansion or contraction of the body under examination, are independent of the instrument which holds it.

The *manometer*, which indicates the pressure in the instrument, is

seen under the steel block which carries the tubes. It is simply a mercurial thermometer with a very thick bulb. The scale on it is an arbitrary one, and its value as a measure of pressure is fixed by observing its reading when the principal piezometer which I used during the voyage of the "Challenger" was in the receiver. This piezometer, known as C No. 1, contained distilled water, and from very many carefully executed experiments at depths from 800 fathoms (1440 metres) up to 2500 fathoms (4500 metres), made in the South Pacific where the oceanic conditions were most favourable, the apparent compression of distilled water in this particular instrument at the temperature ruling in these depths, which averages in round figures 2° C., and when exposed to measured columns of sea-water, of known quality as regards density, was accurately known. The indications of the manometer are, therefore, equivalent to those of piezometer C No. 1, the standardisation of which was effected under an open-air water column. The observations made with C No. 1 on board the "Challenger," which form the basis of the scale of pressures, are collected in Table I. They are expressed in terms of the apparent compressibility of distilled water deduced from them.

In the table the vertical lines represent apparent compressibility in volumes per million per atmosphere, rising by steps of 1 per million from 45—55, so that all the values of the compressibility falling between say 45 and 46, or 49 and 50 are arranged in one column. Above each entry of apparent compressibility will be found the depth in metres to which the instrument was sent, and the temperature (° C.) of the sea-water at that depth. The depth is expressed in metres because it so happens that the average density of the water in this part of the South Pacific, allowance being made for the vertical distribution of temperature, compression, and salinity, is such that a vertical column of it 10 metres high exercises very exactly the same pressure as 760 mm. of mercury. So that the depth in metres, divided by 10, gives the pressure in ordinary atmospheres. At great depths a very slight correction has to be made; the nature of this will be apparent from the following table, in which, for different depths in metres, D, the pressure P in atmospheres is given :—

D......	1400	2000	3000	4000	5000	6000
P......	139·96	200·14	300·82	401·98	503·62	605·75

Owing to the preponderance of water of low temperature and of very uniform salinity in a vertical column of water in any part of the open ocean, the pressure exercised by it per thousand metres does not differ appreciably from 100 atmospheres.

Inspection of Table I shows at once in which column the true value of the apparent compressibility is most likely to be found. It is the one which includes values between 49 and 50. Outside of this

column it is only the adjacent one containing values between 48 and 49 which enters into competition. The mean of all the values in these two columns is 49·16, and this figure forms the basis of the measurement of pressure in this investigation, and it is used in interpreting the pressure-value of the readings of Piezometer C. No. 1, when being compared with those of the manometer used for the ordinary measurements of the pressure in the apparatus.

The change of apparent compressibility of water with change of temperature for the small range of temperatures with which we are concerned was found in 1880 to be at the rate of 0·33 per degree (Celsius), and this figure is used in the present research.

Micrometers.—The same microscopes and micrometers, which served in 1880, were again used in this research. Their value was determined by reference to a stage micrometer, ruled into hundredths and thousandths of an inch. This was then verified at the National Physical Laboratory. The changes of length measured by the micrometers are therefore given in terms of the standard inch; and, it may be added, the values attached to the readings of the micrometers in 1880 were exactly the same as those now found by reference to the standard of the National Physical Laboratory.

In the microscope which was always placed on the left hand, one division was equivalent, on the stage, to 0·0004219 inch. In the one on the right hand one division was equivalent to 0·0004167 inch on the stage.

As the contractions or expansions are given directly in terms of the inch, the total length of the rod is given in inches also. In order to bring the ends into a suitable position for observation with the microscopes the length of the rod or wire had to be not less than 75 or greater than 75·5 inches. The actual lengths were measured exactly in each case. The average was 75·32 inches (1·913 metres).

To facilitate the observation of the ends through the thick glass tube a piece of microscopic covering glass was moistened with a drop of water and laid horizontally on the tube, producing the same effect as if a flat surface had been ground and polished on it.

The effect observed and measured is the lengthening of the rod when the pressure is relieved. As the compressibility of solids is very small, the highest pressures have been used which were found to be compatible with the reasonable persistence of the glass terminals; the usual pressure was in the neighbourhood of 200 atmospheres. Very few of the glass terminals stood over 300 atmospheres. The pressures actually chosen were as nearly as possible those at which the manometer had been compared with the "Challenger" piezometer.

The body under observation is in the form either of a rod or a wire. If it is in the form of a rod then it is fitted with wire ends of sufficiently small calibre to enable them to enter the glass terminals.

Table I.—The Apparent Compressibility of Water in Glass, as observed in Piezometer C. No. 1, on board H.M.S. "Challenger," in the South Pacific, in October, November, and December, 1875. The observations are arranged in order of apparent compressibility, which is expressed in volumes per million per atmosphere. Above each entry of the apparent compressibility is, on the left, the depth, in metres, of the water at the particular station, and, on the right, its temperature, in Celsius's degrees.

	Apparent compressibility per million per atmosphere.									
Apparent compressibility.	45–46	46–47	47–48	48–49	49–50	50–51	51–52	52–53	53–54	54
	2475 1°·9 45·0	1800 2°·6 46·8	1890 2°·8 47·1	4140 1°·6 48·7	1620 2°·4 49·6	1800 2°·4 50·6	2700 1°·9 51·0		1800 3°·1 53·4	2880 1°·8 55·5
		2385 2°·2 46·8	3195 1°·9 47·3	3330 1°·6 48·1	1620 2°·7 49·5	1800 2°·4 50·8	2700 2°·3 51·7			
			4005 2°·0 47·8	4050 1°·4 48·0	2880 1°·8 49·8	1800 2°·3 50·1				
			2610 2°·0 47·0	2700 2°·0 48·9	2520 2°·2 49·4					
				1620 3°·0 48·8	3645 1°·3 49·7					
				2700 2°·0 48·4	1440 3°·2 49·65					
				2700 2°·0 48·15	4085 1°·4 49·2					
					2700 1°·8 49·75					
					3285 1°·8 49·1					
					3195 1°·95 49·0					
					1800 2°·7 49·8					
					3240 2°·2 49·7					
					1800 2°·8 49·0					
Mean values ..	2475 1°·9 45·0	2090 2°·4 46·8	2925 2°·18 47·3	3035 1°·95 48·56	2540 2°·17 49·48	1800 2°·4 50·5	2700 2°·1 51·35		1800 3°·1 53·4	2880 1°·8 55·5
				2700 49·16 2°·1						
Number of observations	1	2	4	7	13	3	2	0	1	1
				20						

During an experiment with a rod it contracts while the pressure is being raised, and expands again when the pressure is relieved. The steel tube which holds it, however, acts in the opposite sense, it expands while the pressure rises and contracts while it falls. If the two surfaces were perfectly smooth, one half of the change of length would be measured at the one end and the other half at the other end. As the surfaces are not perfectly smooth, this does not usually occur. Moreover the steel tubes are prolongations of the central steel block which holds them. The block is bored with holes at right angles to each other in the three principal directions. Consequently for a distance of about an inch and a half in passing through the block the rod is not supported at all. With the exception of this small portion, however, the rod is supported throughout the whole of its length by the steel tube. Now, although it is thus nominally supported equally throughout the whole of its length, we know that in reality this is pretty certain not to be the case. At some place, either in the right arm or in the left arm of the apparatus, the rod is sure to bear more heavily than in any other part. The contraction under pressure and the expansion under relief of pressure will then apparently take place as from this point as origin. Supposing this point itself to be motionless, it is evident that the change of length measured at the two ends will be in the same proportion to each other as would be the arcs which they would describe if the rod were a lever oscillating on the point as a fulcrum. As there is no support at all at the centre, this point must lie on one side or on the other of it and the motions of the ends must be unequal. But the fixed point of the tubular receiver is the central block; therefore any point in, let us say, the right-hand tube will, when pressure is being raised, move to the right, and, on relief of pressure, retreat by an equal amount to the left. Consequently when we observe and measure the change of position of, for instance, the right-hand extremity of the rod, when the pressure is relieved, that change of position is composed of two motions, the expansion of the part of the rod which lies between the right-hand extremity and the point in it whose motion with respect to the steel carrying tube is *nil*, along with the proper motion of that point. Similarly, when we measure the change of position of the left-hand end, it also is composed of two parts, the expansion of the part of the rod which lies between the left-hand extremity and the same point in the length of the rod where its motion with respect to the steel tube is *nil*, along with the proper motion of that point. But at the left-hand end the motion of expansion is to the left, and at the right-hand end it is to the right, while the proper motion of the position of the common point on the rod and on the tube is always in one direction, and in this case, to the left. Therefore the distance measured in the right-hand microscope is the expansion of the portion of the rod which lies to the right of

the point on it which is motionless relatively to the tube *minus* the proper motion of this point: and the distance measured at the left-hand end is the expansion of the remainder of the rod *plus* the proper motion of the common point. Consequently the algebraic sum of the two motions measured is the expansion of the rod under the relief of pressure.

When the substance is used in the form of a rod, as, for instance, in the case of glass, its ends are drawn out into wires, such that they can enter and be visible in the glass terminals. What we really measure then is the change of length under change of pressure of the axial glass wire in the rod, which may be looked on as a *fascine* of a very large number of similar but somewhat shorter wires. The sole function of these other wires is to maintain the wire that falls under observation in an axial position. It is obvious that this function can be performed with equal efficiency by wires of any other material, and that the conditions are in no way altered if these are fused into a tube of which the wire to be measured may be regarded as the core. Consequently by my method the linear compressibility of a solid can be determined as well on a wire as on a rod; and there is no limit to the thinness of the wire, so long as it can be handled, and be perceived in the microscope.

These two conditions are, in a way, antagonistic, because for the microscope the finest possible point is desirable, while for the handling of the wire a sensible thickness is essential. Only in the case of glass can a good working compromise be effected, because the wire which enters the glass terminal can be drawn out at the end to the finest possible hair, and the end of the hair can be fused into the minutest possible sphere, which can then be observed in the microscope with the sharpness with which a barometer can be read with a good telescope.

When the substance under observation is in the form of a wire, it lies in a glass tube which fits the bore of the steel tube as closely as possible. Its bore is a very little larger than that of the glass terminals, or about 1 mm. This tube acts as a bearer, and its length is as nearly as possible equal to the distance which separates the inside ends of the glass terminals when in position. When the pressure in the apparatus is raised, both the wire and the glass tube which carries it are shortened, while the steel tube which carries both of them is lengthened, and when the pressure is relieved the reverse takes place. The glass tube behaves exactly like the glass rod, that is, it is liable to a slight motion of translation. Similarly, the wire, which is carried by the glass tube, generally expands and contracts under pressure at a less rate than does the glass, producing again a slight apparent motion of translation. But again, as in the case of the rod, the algebraic sum of the observed motions is the expansion or contraction of the wire.

There is an advantage in having a very slight leak in the apparatus. The routine of an observation is then that the observer in charge of the pump and the manometer gets the pressure up somewhat higher than that desired; he then settles himself with the relieving lever in his hand and calls out as the mercury in the manometer in falling passes each division. The observers at the microscopes read their micrometers at the same moment. When the pressure has fallen a little below the desired pressure, the pressure is very carefully relieved, and the readings of the micrometers and of the manometer are taken at atmospheric pressure. The algebraic sum of the movements of the two ends on the micrometers gives the linear expansion of the body which has taken place, and the difference of the two readings of the manometer gives, when interpreted by the help of Piezometer C. No. 1, the difference of pressure which has caused the expansion. The micrometer measurements are then reduced separately to their absolute values in terms of the inch. The algebraic sum then gives the linear expansion in terms of the inch. It is then divided by the length of the rod or wire in inches and by the pressure in atmospheres; the resulting quotient is the linear compressibility of the metal or other substance. Multiplying this by three, we obtain the cubic compressibility of the substance, if truly isotropic.

It will be evident that, to work with this instrument, three observers are necessary, namely, one for each microscope, and one to raise and relieve the pressure and observe the manometer. I was fortunate in being assisted during this investigation by Mr. Andrew King, who was formerly my regular assistant, and is now of the Heriot-Watt College, Edinburgh, and by Mr. J. Reid, Demonstrator in the chemical laboratory of that institution. These gentlemen gave up their Christmas vacation for this work, and I owe them a deep debt of gratitude for the willingness and the efficiency of their help. The metals experimented with have been used in the form of wire, and the size chosen was No. 22 of the standard wire gauge (S.W.G.). In the case of aluminium, however, the size was No. 20. The dimensions corresponding to these numbers are given in the following table :—

No. of wire.	Diameter of wire.		Sectional area of wire.	Length of 1 c.c.
S.W.G.	inch.	mm.	sq. mm.	metre.
20	0·036	0·914	0·656	1·524
22	0·028	0·711	0·397	2·519

The degree in which the actual wires corresponded with the tabular specification was checked by weighing measured lengths of them.

The weight of 1 metre of each wire was as follows:—Platinum, 8·156 grammes; gold, 7·320 grammes; copper, 3·375 grammes; aluminium (No. 20), 1·642 grammes; and magnesium, 0·552 gramme. Neglecting the magnesium which, being pressed and not drawn, is very uneven in its calibre, these figures show that the actual wires were very slightly smaller than they should be by the gauge. Thus, in the case of the platinum wire 1 c.c. occupies 2·636 metres (lineal) instead of 2·519 metres as by the table.

The platinum and gold wires were pure specimens obtained from Messrs. Johnson and Matthey in the year 1880. The copper was "high conductivity" copper, and it as well as the aluminium and magnesium wires were of the best quality obtainable at the present day. The platinum and gold wires were heated to redness over a Bunsen lamp before use, so that they were thoroughly annealed. The aluminium wire was also heated, though to a much lower temperature, so as to soften it. The other metals were used in the state in which they were supplied. All the wires were straightened, but not stretched, before use.

The temperature of the wires during the operations was always that of the laboratory, and every care was used to keep it as uniform as possible, and it was as nearly as possible that of the air outside. Working in the middle of winter and in a comparatively high latitude, I hoped to be able to do so in conditions which, as regards temperature, would be similar to those which obtain in the depths of the sea, but the extraordinary mildness of the weather this year made it impossible, and the temperatures fell, mostly between 9° and 11° C.

The results of the investigation are set forth in detail in Tables II to VI, and they are summarised in Table VII.

Table II.—Platinum. Date, January 9, 1904. Temperature, 7° C. Wire No. 22 S.W.G. Length, 75·35 inches.

No.	Pressure, P.	Changes of length.			Compression per million, $10^6 \frac{s}{75 \cdot 35} = S$.	Linear compressibility, S/P = λ.
		Right arm, r.	Left arm, l.	Sum, $r + l = S$.		
	atm.	in.	in.	in.		
1	204	0·003750	−0·000844	0·002906	38·57	0·188
2	204	0·003750	−0·000970	0·002780	36·88	0·180
3	204	0·003750	−0·000928	0·002822	37·45	0·184
4	300	0·005292	−0·001181	0·004111	54·56	0·182
						0·1835

Table III.—Gold. Date, January 10, 1904. Temperature, 10°·6 C.
Wire No. 22 S.W.G. Length, 75·4 inches.

No.	Pressure, P.	Changes of length. Right arm, r.	Left arm, l.	Sum, $r+l = \text{S}$.	Compression per million, $10^6 \frac{s}{75 \cdot 4} = \text{S}$.	Linear compressibility, $\text{S/P} = \lambda$.
	atm.	in.	in.	in.		
1	231·5	0·005208	−0·000591	0·004617	61·21	0·264
2	230·0	0·005208	−0·000970	0·004238	56·20	0·244
3	230·0	0·005417	−0·000844	0·004573	60·64	0·264
4	204·0	0·005000	−0·000590	0·004410	58·48	0·287
5	247·0	0·005834	−0·001181	0·004653	61·70	0·254
6	230·0	0·005208	−0·001094	0·004114	54·55	0·237
7	238·5	0·005000	−0·000422	0·004578	60·70	0·255
8	238·5	0·005000	−0·000422	0·004578	60·70	0·255
9	238·5	0·005208	−0·000633	0·004575	60·66	0·254
10	273·5	0·006042	−0·000548	0·005494	72·85	0·264
11	273·5	0·005834	−0·000211	0·005623	74·56	0·273
12	273·5	0·006042	−0·000591	0·005451	72·28	0·264
13	273·5	0·006042	−0·000464	0·005578	73·96	0·270
14	273·5	0·006042	−0·000717	0·005325	70·61	0·258
15	273·5	0·006250	−0·000717	0·005533	73·37	0·261
16	273·5	0·006042	−0·000506	0·005536	73·41	0·268
17	269·0	0·005834	−0·000422	0·005412	71·76	0·267
18	273·5	0·006042	−0·000548	0·005494	72·85	0·266
						0·260

Table IV.—Copper. Date, January 9, 1904. Temperature 10° C.
Wire No. 22 S.W.G. Length, 75·3 inches.

No.	Pressure, P.	Changes of length. Right arm, r.	Left arm, l.	Sum, $r+l = \text{S}$.	Compression per million, $10^6 \frac{s}{75 \cdot 3} = \text{S}$.	Linear compressibility, $\text{S/P} = \lambda$.
	atm.	in.	in.	in.		
1	195·5	0·005664	−0·001687	0·003980	52·85	0·270
2	230·0	0·006334	−0·001687	0·004647	61·70	0·268
3	195·5	0·005875	−0·001814	0·004061	53·93	0·276
4	195·5	0·006125	−0·001772	0·004353	57·81	0·296
5	247·0	0·007417	−0·001856	0·005561	73·85	0·299
6	230·0	0·006750	−0·001434	0·005316	70·60	0·307
7	282·5	0·007751	−0·001519	0·006232	82·76	0·293
						0·288

Table V.—Aluminium. Date, January 11, 1904. Temperature, 9° C. Wire No. 20 S.W.G. Length, 75·35 inches.

No.	Pressure, P.	Changes of length. Right arm, r.	Left arm, l.	Sum, $r+l$ = S.	Compression per million. $10^6 \frac{s}{75 \cdot 35}$ = S.	Linear compressibility, S/P = λ.
	atm.	in.	in.	in.		
1	195·5	0·005542	0·002616	0·008158	114·22	0·584
2	161·5	0·004900	0·002152	0·007052	93·58	0·579
3	230·0	0·006667	0·002742	0·009409	124·86	0·543
4	178·5	0·005334	0·002109	0·007443	98·77	0·553
5	256·0	0·007251	0·002995	0·010246	135·96	0·531
						0·558

Table VI.—Magnesium. Date, January 17, 1904. Temperature, 9° C. Wire No. 22 S.W.G. Length, 75·2 inches.

No.	Pressure, P.	Changes of length. Right arm, r.	Left arm, l.	Sum, $r+l$ = S.	Compression per million, $10^6 \frac{s}{75 \cdot 2}$ = S.	Linear compressibility, S/P = λ.
	atm.	in.	in.	in.		
1	204	0·009167	0·007120	0·016288	216·61	1·062
2	204	0·010001	0·006202	0·016203	215·48	1·056
3	204	0·009917	0·006329	0·016246	216·07	1·059
4	204	0·010418	0 005991	0·016409	215·57	1·057
5	204	0·010543	0·005442	0·015985	212·60	1·042
6	204	0·011251	0·004852	0·016103	214·16	1·050
						1·054

Table VII.—Summary.

Substance.	Year.	Atomic weight.	Density.	Compressibility. Linear.	Cubic.
Platinum	1904	194	21·5	0·1835	0·5505
Gold	,,	197	19·3	0·260	0·780
Copper	,,	63	8·9	0·288	0·864
Aluminium	,,	27	2·6	0·558	0·1674
Magnesium.......	,,	24	1·75	1·054	3·162
Mercury	1875	200	13·6	1·33	3·99
Glass, flint	1880	..	..	0·973	2·92
,, ,, ...	1904	..	2·968	1·02	3·06
,, German	,,	..	2·494	0·846	2·54

In the summary, Table VII, the compressibilities of English flint glass and of the glass of which ordinary German tubing is made as well as that of mercury have been included for purposes of comparison. The compressibility of mercury rests upon a large number of observations made in the "Challenger,"* by which its apparent cubic compressibility was found to be 1·5 per million per atmosphere. The piezometers which were used for this purpose were made by myself on board. The divided stems were of lead glass, because I had no other, and the bulbs or reservoirs, which had a capacity of about 20 c.c., were made of German glass, for the same reason. I have, therefore, applied to the values then found for the apparent compressibility of mercury, the value of the absolute compressibility of German glass found in January of this year, and the result is that the absolute cubic compressibility of mercury at temperatures between 1° and 3° C. is 3·99.

With regard to the metals quoted in the tables, the figures speak for themselves. The number of different metals is very small and, until the investigation has been extended so as to include at least the greater number of the metals which can be easily procured in the form of rod or wire, it is not likely that any very general features or laws will be apparent. It will, however, be observed that in the case of the five metals used as wire, their compressibility increases as their density and atomic weight diminish, yet there is no reason to suppose that the compressibility is a continuous function of the atomic weight, like the specific heat. Mercury, although in the fused state, shows this clearly. But besides this, it happens that two pairs out of the five metals, namely, platinum-gold and aluminium-magnesium, are contiguous in the atomic weight series, yet the compressibility of magnesium is, roughly, double that of aluminium, and the compressibility of gold is half as much again as that of platinum. If, however, we compare gold and copper, which occupy parallel positions in Mendeléieff's scheme, we see that they are very much alike, and the same holds with regard to magnesium and mercury which occupy a homologous position. If these facts indicate anything more general, we should expect the metals of the palladium and the iron groups to have a low compressibility like platinum, zinc and cadmium to have a very high compressibility like magnesium, and thallium an intermediate but still considerable compressibility like aluminium.

It will be observed that the two kinds of glass mentioned in Table VII are more compressible the greater their density. This may, however, be due to a specific feature of the oxide of lead which enters largely into the composition of the flint glass.

It is obvious that there is here a great field for interesting research, and fortunately the method is capable of great refinement; only, the successful application of it requires considerable manipulative skill,

* 'Chem. Soc. Jour.' (1878), vol. 33, p. 453.

as well as great patience. The necessity to have, as part of the apparatus, two glass tubes which are exposed to the high pressure on the inside only, introduces an element of chance into the work which is sometimes annoying and sometimes exciting. It is impossible to say beforehand whether a particular glass terminal will stand or not. It is necessary to be provided with a large reserve of them before beginning work, and when one fails another is put in its place without loss of time. Hitherto I have taken no particular care of my glass terminals, because I can always depend on finding plenty of them which will stand from 200—300 atmospheres, and there is abundance of work to be done at these pressures. When, however, it is desired to use higher pressures, it will be prudent to take some measures for preventing the points of the wires scratching the internal surfaces of the terminals. When some precaution of this kind has been taken, casualties will be less frequent, and the attainment of higher pressures will be merely a question of how many glass ends the observer is prepared to sacrifice in the service.

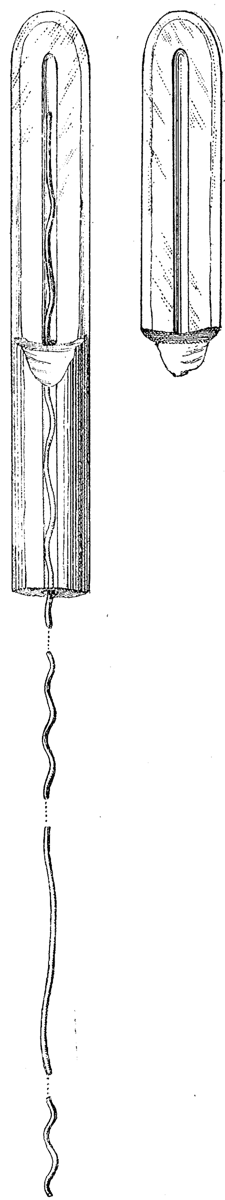
In the work connected with this paper, which extended over the greater part of 4 weeks, fifteen glass terminals gave way; and oddly enough, the failures were as nearly as possible equally distributed between the two ends; eight of them fell to the left arm and seven of them to the right arm. The bursting of a terminal causes no inconvenience beyond the trouble of replacing it, because the construction of the instrument enables air to be completely excluded from it, and the quantity of water in it to be kept within such limits that its resilience is of no account. When a tube bursts it usually splits longitudinally up the middle into two slabs. One of these almost always remains entire, the other is sometimes broken into fragments, but there is never any projection of material unless the instrument has been carelessly put together and air admitted.

Microseismic Effects.—In a research like the present where the primary object is the numerical determination of a physical constant, the secondary phenomena which reveal themselves are often of equal and sometimes of greater interest, because they generally affect preferentially the natural history side of physics. To this class belong the phenomena observed in connection with the behaviour of ice under the relief of high pressure in my earlier investigation.* In the present case the frequent bursting of the glass terminals afforded the opportunity of observing another and very interesting phenomenon. It is illustrated in fig. 2. It was first noticed when copper wire was being experimented with. The pressure had been raised to 300 atmospheres, and had begun to fall when the tube gave way. On proceeding to replace the broken tube with another I was astonished to find the copper wire twisted into a regular spiral

* 'Roy. Soc. Edin. Trans.,' vol. 29, p. 598.

in the tube. It made three complete turns in the length of an inch, and the undulatory form was visible throughout one-half of the length of the wire. Instead of fixing new glass terminals, I cut off the end of the copper wire, which showed this curious seismic effect, and put another wire in its place. An exactly similar effect was produced on the magnesium wire, when a glass terminal burst; only the effect was even more marked. The spiral produced in the glass end was closer, and, indeed, the wire had been shoved over itself and broken, for magnesium wire is very brittle. The undulations of greater amplitude extended through the whole length of the wire, and there were *maxima* at distances of about 35 cm. and 85 cm. from the seat of the explosion. The bursting pressure in this case was no more than 150 atmospheres, yet the effect produced was very much greater than it was in the case of copper.

FIG. 2.



The experiments with gold and aluminium were carried out without the loss of a terminal.

In the case of platinum, a terminal burst at about 250 atmospheres, but it produced no apparent seismic effect. On the last day of my experiments I proposed to determine the compressibility of a wire of mild steel, but, owing to hurry in putting the apparatus together, it was impossible to get any satisfactory observations, but one of the terminals burst, and at a pressure over 250 atmospheres. Here again there was no seismic effect. The platinum wire had been thoroughly annealed before being used, and the mild steel wire was as soft and ductile as copper, yet, though copper showed the seismic effect beautifully, it was imperceptible in both platinum and steel. Before the experiment with the steel, I supposed that the high density of platinum caused the shock to be opposed by more inertia than it could overcome, but the density of steel is less than that of copper, therefore its immunity to shock must be due to something other than its density.

The open ends of the glass terminals which are inside of the watertight collars are cut sharply off and the edges are not rounded in the

flame. Special directions were given to the glass blower about this, because the effect of it would be the production of considerable tension in that part of the glass. Notwithstanding my directions, some of the tubes were rounded off in the lamp and the effect was as I had foreseen. The only one of these ends which I used burst. In the case of ends which have been cut off and not heated, the fracture is confined to the part of the tube outside the apparatus. In the case of the end with rounded edges the outside part was fractured in the ordinary way, and in addition the rounded portion, which was exposed to no difference of pressure, exploded out of sympathy, much after the fashion of a Prince Rupert's drop.

I am continuing this investigation, and I hope shortly to be in a position to be able to communicate further results to the Society.

CROONIAN LECTURE.—"The Chemical Regulation of the Secretory Process." By W. M. BAYLISS, F.R.S., and E. H. STARLING, F.R.S. Received March 21,—Read March 24, 1904.

In the complex reactions which make up the life of an individual, and the evolution of which has been the determining factor in the individual's existence, we may distinguish two main types; though, as in all attempts at classification of biological processes, the line of division between the two types must be more or less indistinct.

In the first place we have those reactions which depend for their production on some special structural arrangement, and are therefore determinant factors in the evolution of form. In some cases the adaptive production of organs or protective mechanisms may be associated with a direct chemical reaction, as in the formation of protective tissues. In most cases, in higher animals at any rate, such an adaptation will be intimately associated with the development of the central nervous system, of which the peripheral parts of the body must be regarded as the executive mechanisms. In general, however, we may say that this type of adaptation is dependent on the adaptive *growth* of cells.

The second type, the more primitive of the two, involves, in the first place, not so much a change in the growth or arrangement of cells, as a change in the metabolism of pre-formed cells or structures. It may, perhaps, be looked upon as a preliminary to the first type, namely, structural change. It is, however, of special interest, since its mechanism is subject to analysis by physiological methods. Instances of chemical adaptation may again be divided into two groups. In the first place we have the chemical adaptation to the

Fig. 1.

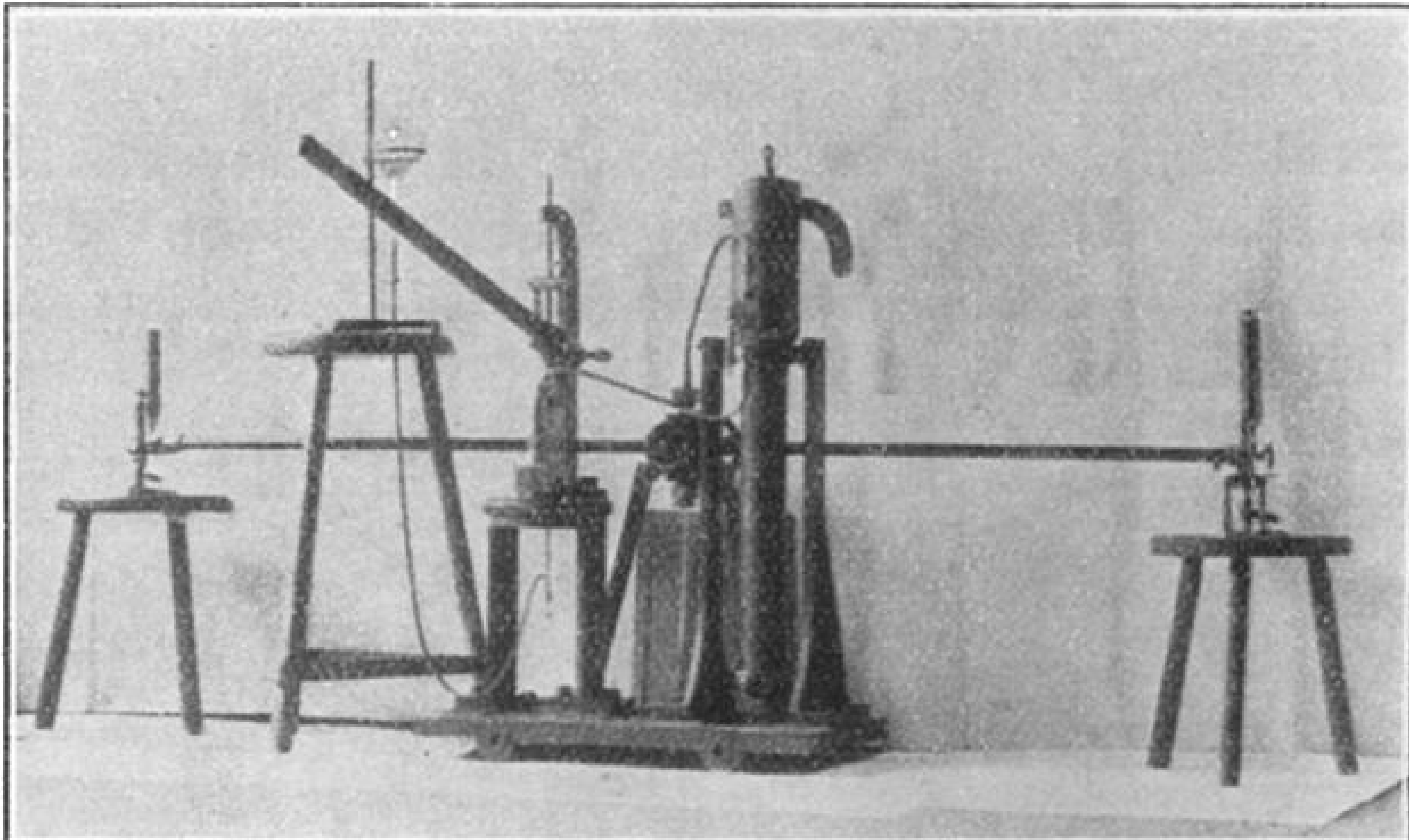


FIG. 2.